Mem. S.A.It. Suppl. Vol. 19, 67

Memorie della
Supplementi

The European Solar Telescope: project status

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Abstract. The European Solar Telescope (EST) project foresees the realization of a 4 - meter solar telescope, characterized by an optical design and by a suite of instruments optimized for spectropolarimetric measurements from near infrared to near UV. The aperture, the site at the Canary Islands, the adaptive optics and the multi conjugate adaptive optics for extended sources integrated along the optical path, the set of instruments and the post facto image processing techniques, will allow us to study the interaction between the plasma and the magnetic field in the solar atmosphere at resolutions comparable to the photon mean free path in the photosphere. EST will be operational contemporarily to major ESA and NASA space missions for the study of the Sun and of its activity.

Key words. Sun: photosphere – Sun: chromosphere – Sun: magnetic fields – Instrumentation: high angular resolution – Instrumentation: telescopes

1. Introduction

In the past twenty years the possibility to perform observations with high angular and temporal resolution, provided by space-borne satellites (YOHKOH, SOHO, TRACE, RHESSI, HINODE, STEREO) and by ground-based telescopes (THEMIS, VTT, SST, DOT, DST) allowed solar physicists to achieve important progresses in the comprehension of many physical processes occurring on the Sun.

As an example, we report in Fig. 1 data of a sunspot acquired at the SST that shows the presence of dark cores in the penumbral fibrils. These features were firstly discovered on SST data obtained with an angular resolution of ~ 0.2 arcsec.

We also recall the progress achieved in recent years in numerical simulations of astrophysical processes, thanks to the access to new high performance computing facilities, that also provided us the opportunity to compare the results obtained by simulations with the observations, often opening new paths to the understanding of the physical mechanisms taking place in solar phenomena.

Therefore, we are now able to describe in more details the physical processes occurring in many solar phenomena, like those concerning the formation and evolution of active regions on the Sun, the impulsive release of energy occurring during solar flares, the enormous expulsion of plasma clouds during coronal mass ejections (CMEs), the continuous flow of particles from the solar corona, i.e., the solar wind, and so on.

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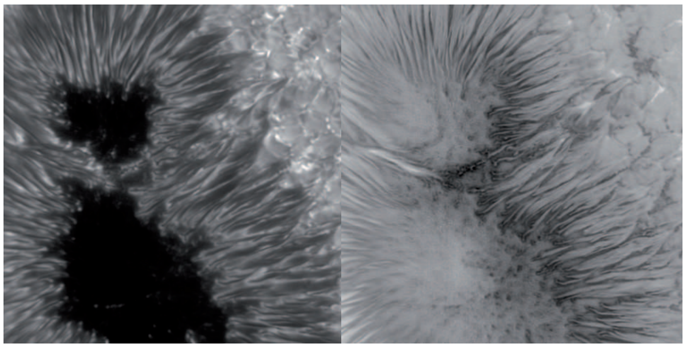

Fig. 1. Sunspot observed by the Swedish Solar Tower (SST) in the blue and red wings of the magnetically sensitive Fe I line at 630.2 nm on Sept 12, 2006. The left-hand image represents the average intensity, the right-hand image the difference in circular polarization (normalized to intensity) of the wings. The spatial resolution of these images is close to 0.2 arcsec. Dark penumbral cores, discovered with the SST, are clearly seen in both intensity and polarization signal (Scharmer et al. 2002).

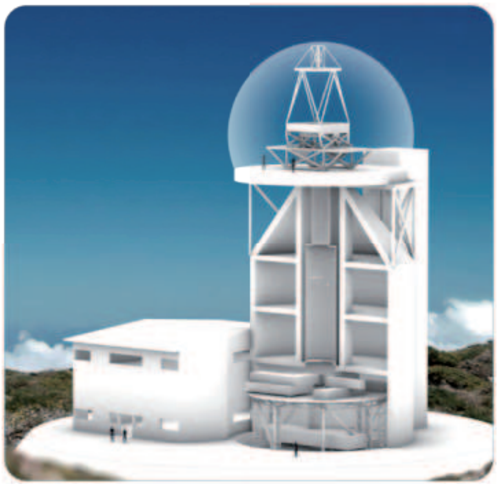

Fig. 2. Schematic view of the EST telescope. The 4-m alt-azimuthal telescope is located on the top of a $\sim$ 30-m tower. The light beam is directed via transfer optics to the instrument laboratory located at ground level (Cavaller et al. 2010).

However, many problems remain unresolved, like for instance those relevant to the realization of a complete, self-consistent picture of the mechanisms at the basis of the cyclical magnetic activity of the Sun, those concerning the mechanisms responsible for the chromospheric and coronal heating, the phases of sunspots decay and magnetic field diffusion, or the trigger mechanisms of solar flares, etc.

For instance, if we take into account the mechanism that is considered to be at the basis of the sudden energy release taking place in eruptive phenomena, i.e, magnetic reconnection, it is clear that a deep understanding of this phenomenon relies on the possibility to have major information on the reconnection site, that is on the current sheet where the reconnection occurs. However, all the models on magnetic reconnection developed so far, indicate that the size of the current sheet is well below the current angular resolution limit. Therefore a greater spatial resolution than that provided by the operating solar telescopes is needed to detect signatures of the presence of these structures, where resistive effects can take place.

In this scenario, it is also worthwhile to mention that in recent years it has become increasingly clear that the study of physical processes occurring on the Sun can provide useful hints for a better understanding of phenomena taking place in other astrophysical contexts. The study of stellar activity, as an example, has received noticeable inputs from our knowledge of the magnetic activity on the Sun, both as far as the dynamo mechanism is concerned, as well as for the occurrence and evolution of stellar spots and stellar flares.

Besides, magnetic reconnection of field lines, that has been deeply investigated on the Sun, is now taken into account by several authors who are trying to extend the results of

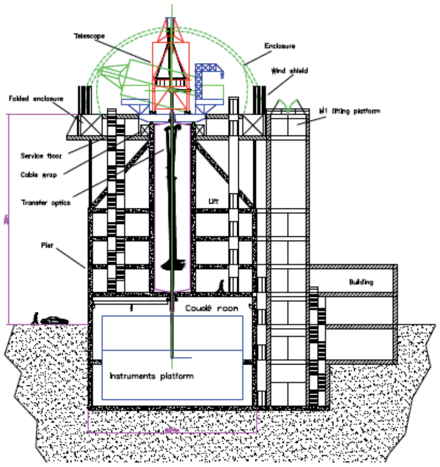

Fig. 3. Layout of the EST telescope (from Cavaller et al. 2010).

solar studies to the case of binary systems showing activity phenomena (see, e.g., Zhang 2007). On the other hand, the physical mechanisms at the basis of collimated jets of plasma in the reconnection sites investigated in the solar context, have also been invoked to explain the presence of non-stationary jets of plasma in black holes surrounded by accretion disks (Yuan et al. 2009).

As a consequence, in a general view of the Sun as a cosmic laboratory where the interaction of plasma and magnetic field can be studied in close detail, it is expected that many of the above mentioned solar and non-solar questions might be solved when higher spatial, temporal and spectral resolution observations of the Sun will be carried on. This constitutes the premise to build a new generation solar telescope: the European Solar Telescope (EST), with an aperture of 4 meters (see Fig. 2), to reveal the fine aspects of processes that act on stars and in laboratories.

Table 1. Solar Telescope apertures

Telescope	Aperture (m)	Site
DOT	0.45	La Palma
VTT	0.70	Tenerife
DST	0.75	USA
THÉMIS	0.90	Tenerife
SST	0.98	La Palma
Gregor	1.50	Tenerife
Mc Math	1.60	USA
NST	1.60	USA

Currently, the ground-based solar telescopes operating in Europe and in USA have an aperture below or equal to 1.6 meter (see Table 1), but there will be a significant increase in the angular resolution with the operation of a 4-m class telescope.

Moreover, taking into account that detailed information on the magnetic field characteristics can be inferred from the polarization of the spectral line profiles, we also need spectropolarimetric measurements at the highest angular resolution achievable, which require the detection of a sufficient number of photons to reduce the noise level below the amplitude of the polarimetric signals. In particular, to study the photospheric magnetic fields, a signal-to-noise ratio should be of the order of or greater than 10^3.

To stress how this requirement is shared by the scientific community, we recall that in the document a Science Vision for European Astronomy the following goal was identified: *to establish the basic mechanisms of magnetic field generation and to forecast transient events that directly or indirectly affect life on Earth; to detect and identify the mechanisms by which energy is transferred from the solar surface that heats the upper solar atmosphere and eventually accelerates the solar wind* (see http://www.astronet-eu.org).

On the basis of these premises, EST is at the highest priority in medium-size ground-based Outstanding Projects in the ASTRONET Road-Map.

The EST project is promoted by the european solar physics community by means of EAST (European Association for Solar telescopes), a consortium formed by research organizations from 15 European countries (Austria, Croatia, Czech Republic, France, Germany, Great Britain, Hungary, Italy, The Netherlands, Norway, Poland, Slovakia, Spain, Sweden and Switzerland), aimed at the de-

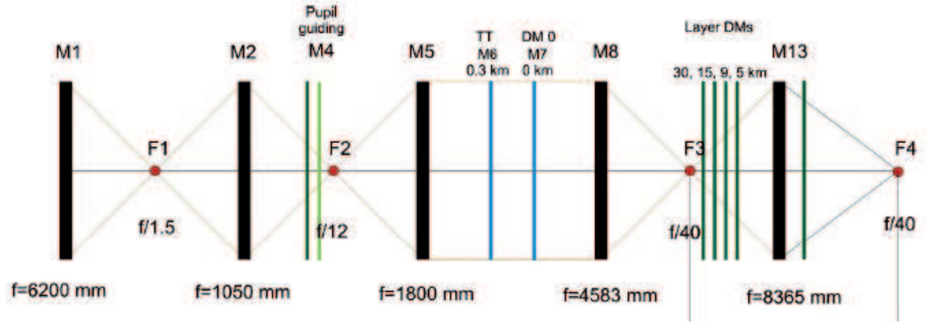

Fig. 4. Scheme of the current EST optical design (Cavaller et al. 2010).

velopment, realization and management of the telescope.

The project is currently in the conclusive phase of the Conceptual Design Phase, financed by the European Commission in the framework of FP7 – Capacities Specific Programme – Research Infrastructures (Collados et al. 2008, 2010a). The project is lead by the Institute de Astrofísica de Canarias, and is developed by 29 european partners (14 research institutions and 15 companies).

2. The Scientific Objectives

The aim of the EST telescope is to obtain high-spatial, high-temporal, accurate, and simultaneous multi-wavelength polarimetric observations of the photosphere and chromosphere, both with narrow-band filters and 2-D spectrographs, in the spectral range from the visible to the near-infrared (350 to 2300 nm).

The main scientific objectives of the project are (see, e.g. Socas Navarro et al. 2010):

– How does the magnetic field emerge to the surface and evolve ?
– How is the energy transported from the photosphere to the chromosphere ?
– How is the energy released deposited in the upper atmosphere ?
– Why does the Sun have a hot chromosphere?
– What mechanism causes eruptive phenomena (flare, filament eruption, coronal mass ejections) ?

In order to give an answer to these questions the following telescope requirements have been singled out:

– Simultaneous spectropolarimetry of the photosphere and the chromosphere,
– Superb optical quality, with very high throughput (minimum number of optical surfaces),
– Integrated high-order adaptive optics (AO) and multi-conjugate adaptive optics (MCAO),
– Spectrograph capabilities from blue to near-IR with several simultaneous spectral regions (and polarimetric capabilities),
– Narrow-band tunable filtergraphs from blue to near-IR, simultaneously accessible (with polarimetric capabilities),
– Complementary imaging channels of photospheric and chromospheric layers (G-Band, Hα, etc.).

3. The Current Design

The EST Design Phase started in February 2008 to last three years. EST construction is expected to start in 2014 and first light is foreseen in 2019.

The current baseline design of EST is based on a 4-meter class solar telescope characterized by an on-axis Gregorian configuration, in order to achieve a good polarimetric performance. The instruments will be located in a controlled laboratory at the Coudé focus (see Fig. 3). There will be three different types of instruments, each one having various channels in order to observe simultaneously at several wavelengths: a broad band imager, a narrow-band tunable filters spectropolarimeter and a grating spectropolarimeter (Collados et al. 2010b).

The telescope mechanical configuration is alt-azimuthal in order to guarantee a more compact system, a better air flushing on the primary mirror, and to achieve a polarimetric compensated optical design with less optical surfaces, in comparison with the equatorial configuration.

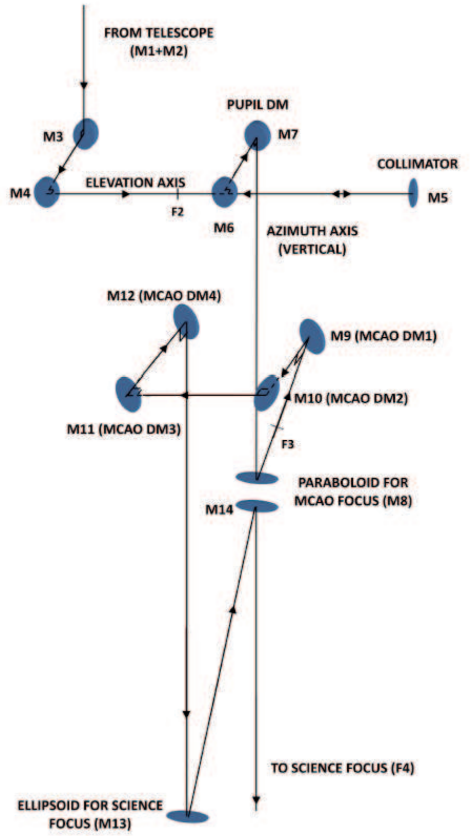

Fig. 5. Schematic drawing of the optical elements of the telescope. Mirrors M3 and M4 (as well as M6 and M7) are polarimetrically compensated. Mirrors M9 to M12 are the MCAO mirrors (from Cavaller et al. 2010).

The telescope design includes also AO and MCAO, consisting of several deformable mirrors at conjugated heights, able to correct for the diurnal variation of the Sun's distance to the turbulence layers, and integrated in the telescope optical path between the primary mirror and the instrument focal plane. The MCAO system will provide diffraction limited optical quality on a field of view (FOV) of 1.87' × 1.87', to maximize the telescope throughput and to provide simultaneously a corrected image at the Coudé focus for the three instruments. It is also foreseen that the MCAO system would be by-passable, enabling higher throughput at the price of correction of a smaller field of view.

An auxiliary full-disc telescope (AFDT, Klvana et al. 2008) is also part of the project. This telescope will be used for the orientation of the observer on the solar disc and in its surroundings, for an easy guidance of the main telescope to a selected target, and it will also perform other tasks to facilitate the work of observers and technical personnel. The AFDT will have an aperture of 150 mm and can operate simultaneously in three spectral regions: Ca II K (394 nm), Hα (656.3 nm), and white light (450 - 460 nm). Moreover, when no observations are carried out at the main telescope, the AFDT will be used for synoptic observations.

3.1. The Telescope Optical Design

The current baseline optical layout consists of 14 polarimetrically compensated mirrors (see Figs. 4 - 5).

The primary mirror M1 is a 4.2 meter parabolic mirror, with a hole in the center having a diameter of 1.4 meters. M1 will have a monolithic glass substrate (Zerodur, ULE or similar material). The optical layout has the elevation axis (line joining M4 and M5, see Fig. 5) placed 1.5 m below the M1 vertex: this configuration facilitates M1 air flushing and allows space enough for the M1 cell and for an adequate placement of the transfer optics train vertically from the telescope to the Coudé focus. Moreover, the elevation and azimuth (line joining M7 and M8) axes are decentered with respect to the telescope optical axis because the optical path is folded in an asymmetric way to produce a polarimetric compensated layout, so that the telescope Mueller matrix is independent of the telescope elevation and azimuth angles.

In Fig. 4 the focus F1 is the Gregorian focus generated by the primary mirror, M1. In F1 a heat-stop will be located, to remove most of the solar light and to allow a field-of-view of (2 - 3) × (2 - 3) arcmin^2. In focus F2, generated by the secondary mirror, M2, the calibration optics will be installed to analyze the polarimetric performance of the telescope, and possibly also polarimetric modulators for polarization measurements. M5 is a collimator that produces an image of the pupil where a deformable mirror, DM (indicated by M7 in Fig. 4), is located to correct for the ground-layer turbulence. The flat mirror M6 will have tip-tilt correction capabilities to avoid image motion.

In Fig. 4 after F3, the focus generated by M8, the conjugated layers where the MCAO mirrors are located, are shown. The present design has four MCAO DMs, conjugated at 5, 9, 15 and 30 km. Mirror M13 generates the science focal plane, F4.

In the present optical design there are three additional flat mirrors: the first two define the elevation axis of the telescope, and to ensure that their instrumental polarization is cancelled (provided their reflection coatings have the same properties), they are placed in such a way that their incidence-reflection planes are perpendicular one to the other (mirrors M3 and M4 in Fig. 5). M6 and M7 (i.e., the tip-tilt mirror and pupil DM, respectively) are arranged in the same geometrical configuration as M3 and M4, being therefore also polarimetrically compensated.

As the elevation axis is defined by the line joining M4 and M5 and the azimuth axis by the line joining M7 and M8, the polarization of the incoming light is not modified, independently of the pointing of the telescope to any direction on the sky. If we consider the transfer optics, which includes the MCAO system, the four high-altitude DMs are also distributed to compensate their polarization properties. M14 is introduced, in addition, to send the light to the instrument room.

The transfer optics can be used as an optical de-rotator if the input optical axis (line joining the centers of M7 and M8) and the output optical axis (line joining M14 and F4) coincide (see Fig. 5). This avoids the inclusion of any optical or mechanical derotating device at instrument level, such as a rotating platform. Instruments can then be kept fixed, ensuring a better stability. This possibility has important advantages for the instruments, for instance the grating spectrographs can be used so that the slit can be kept along the same direction on the sky, ensuring long time series observations.

3.2. The Instruments

The instruments, composed of different channels at the Coudé focus, will be placed in a laboratory with a controlled environment, distributed in two floors (see Fig. 6).

In order to allow simultaneous observations using a flexible number of instruments and channels, a system composed of dichroic and intensity beam-splitters will be used to feed the different instruments channels.

As shown in Fig. 6, in the current design the light is first split by a dichroic beam-splitter D1 in a visible (V) and a near-infrared (NIR) beam. Dichroic beam-splitters D2 and D3 will split further the V beam in three narrower band-passes (390 - 550 nm, 550 - 700 nm, and 700 - 900 nm), where the corresponding broad-band and narrowband channels are placed. Intensity beam-splitters, indicated by inclined lines crossing the beam in Fig. 6, are then used to feed all the instrument channels. The same conceptual design is used for the NIR branch, where an intensity and a dichroic beam-splitter, D4, are included.

The Broad-Band Imager (BBI) is aimed at obtaining high spatial resolution images (better than 0.04 arcsec at 500 nm) at multiple wavelengths and at high frame rate (20 - 100 frame/s) (see Munari et al. 2010). The BBI has two different operational modes (both available in an independent way for each channel):

- high resolution mode (1 × 1 arcmin^2, 0.016 arcsec/pix, 4k × 4k detectors);

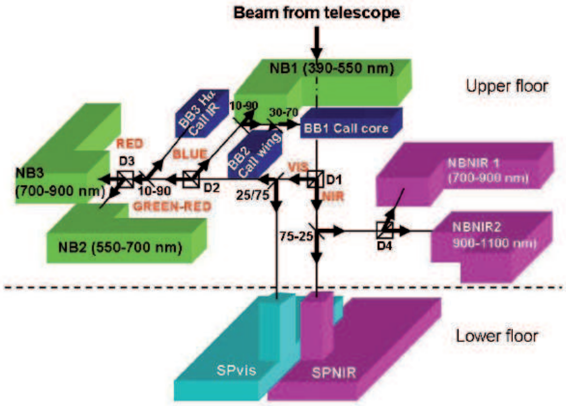

Fig. 6. Schematic drawing of the instrument set-up designed for the EST telescope (from Cavaller et al. 2010).

– large field of view mode (2×2 arcmin^2, 0.03 arcsec/pix, $4k \times 4k$ detectors).

The narrow-band, tunable filter imaging system, is based on Fabry-Pérot interferometers. The etalons could be mounted within the optical light beam either in the collimated configuration (etalons mounted in a parallel light beam near an image of the telescope entrance pupil), or in the telecentric configuration (etalons mounted in the convergent light beam near an image plane).

Four different alternatives have been evaluated so far for the Grating Spectropolarimeters (each having a V and a NIR configuration):

– Long-Slit Standard Spectrograph,
– Multi-Slit Multi-Wavelength Spectrograph,
– Tunable Universal Narrow-band Imaging Spectrograph (TUNIS; López Ariste et al. 2010),
– New generation Multi-channel Subtractive Double Pass (MSDP).

3.3. The Enclosure and the Building

Two different options have been considered for the enclosure: a foldable enclosure and a conventional dome. The choice between these two different options is quite important because the most relevant source of seeing degradation comes from the dome, due to its vicinity to the optical path.

The analysis carried out to date indicates that the completely retractable enclosure can provide better local seeing conditions and would allow the use of a reflecting heat rejecter at the Gregorian focus, but can produce higher wind effect on image quality. Moreover, the primary mirror must be a light-weighted thick mirror, in order to improve its stiffness and ensure a good thermal performance, and tip-tilt and focus correction capabilities must be provided by M2 in order to compensate for wind buffeting effects. With a conventional dome, the effect of wind on image quality would be lower, but the local seeing degradation might be larger and it would be necessary to actively control environmental conditions nearby the telescope.

The pier shall be a tower with a height between 30 and 40 m: the final shape and height will depend on the optical design.

3.4. The Data Handling and Telescope Control System

The EST control system (CS) should guarantee different modes of operation (day-time and night-time observations, maintenance, engineering) by different users, as well as all the operations relevant to the monitoring and controlling of various sub-systems (Ermolli et al. 2010).

The studies carried out until now have demonstrated that the CS should have characteristics similar to those of current medium-sized night-time telescopes. Four different alternatives for the CS software have been evaluated and are still under consideration: i) systems specifically developed for EST; ii) already existing open source systems, such as those realized for ALMA, ATST, GTC; iii) commercial solutions; iv) hybrid systems, using both open source CS and commercial solutions.

4. The Italian participation

The Italian researchers involved in the EST Design Phase financed by EC are $\sim$ 30, distributed over 6 INAF Institutes (Arcetri, Catania, Roma, Trieste Observatories, IFSI-Roma and Telescopio Nazionale Galileo) and 5 Italian Universities (L'Aquila, Calabria, Catania, Firenze, Roma Tor Vergata). In particular, INAF participates in the design of several telescope components and has the responsibility of the Data Handling and Telescope Control Package, as well as of one of the three focal-plane instruments (the Broad Band Imager). The University of Roma Tor Vergata has the responsibility of the heat stop design, carried on in collaboration with the SRS Engineering, and the latter is also involved in the design of the cell of the primary mirror.

5. Conclusions

The EST Conceptual Design Phase will end during 2011 and before this date decisions will be taken on the different alternatives proposed so far. For instance, other optical configurations than the base-line described here are still being studied, in which some of the above properties are varied: different number of MCAO DMs, or no polarimetric compensation at different levels, or no derotation capabilities by the transfer optics. Moreover, the results obtained during the site seeing campaign will allow to take a final decision on the site in the Canary Islands where the telescope will be built (the Teide Observatory in Tenerife or the Roque de los Muchachos Observatory in La Palma).

Acknowledgements. Many researchers are contributing to the EST conceptual design and are included in the words "EST team" appearing in the authors list. Special thanks are due to I. Ermolli for a critical reading of the manuscript. The conceptual design of EST is partially supported by the European Commission through the collaborative project Nr. 212482 *EST: the large aperture European Solar Telescope* under framework programme FP7.

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